Evaluation of model nesting performance on the Texas-Louisiana continental shelf

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[1] A skill assessment of a model of the Texas-Louisiana shelf, nested in a variety of different parent models, is performed using hydrographic salinity data. The nested models show improved salinity skill compared to the same model using climatological boundary conditions, as well as general skill score improvements over the parent models in the same region. Although a variety of parent models are used and these parent models have widely different skill scores when compared with regional hydrographic data sets, the skill scores for the nested models are generally indistinguishable. This leads to the conclusion that nesting is important for improving model skill, but it does not matter which parent model is used. The model is also used to create a series of ensembles, where the local forcing is varied with identical boundary conditions and where the boundary conditions are varied by nesting within the various parent models. The variance in the ensemble spread shows that there is a significant level of unpredictable, nonlinear noise associated with instabilities along the Mississippi/Atchafalaya plume front. The noise is seasonal and is greatest during summer upwelling conditions and weaker during nonsummer downwelling.

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1. Introduction

[2] The northern Gulf of Mexico has been the subject of numerous observational and modeling studies in the past decades. It is a highly important and sensitive region due to regional tourism, fishing, shipping, and oil exploration. Several rivers drain into the Gulf; this study focuses on the Mississippi/Atchafalaya river system, the seventh largest river system by water discharge in the world [*Milliman and Meade*, 1983; *Meade*, 1996]. The Mississippi river basin drains more than 40% of the agricultural land of the U.S. and constitutes a major marine pollution source, inundating the northern Gulf of Mexico with excess nutrients such as nitrogen and phosphorus, leading to eutrophication.

[3] This research is part of the project IOOS-COMT (Integrated Ocean Observing System-Coastal and Ocean Modeling Testbed) of SURA (Southeastern Universities Research Association). A primary motivation for this study is better predictions of seasonal bottom hypoxia over the Texas-Louisiana continental shelf. The goal of this paper is then to assess a hydrodynamic model using metrics of physical environmental conditions relevant to shelf-scale biogeochemical modeling. Predicting the response of the Texas-Louisiana shelf to its main forcings—freshwater from the Mississippi and Atchafalaya rivers, wind, offshore mesoscale features (Loop Current and associated eddies)—is important in understanding the seasonal and interanual variability of shelf hypoxia.

[4] Several recent observational and modeling studies have given insights on the physical processes controlling the temporal and spatial distribution of the Mississippi/Atchafalaya river plume system. The regional bathymetry impacts the behavior of the freshwater plumes and causes spatial differences in stratification [*DiMarco et al.*, 2010; *Schiller et al.*, 2011]. Near the Mississippi delta, the continental shelf is almost absent, but it widens to around 200 km at the Texas-Louisiana border, where the shelf is broad and flat. The freshwater contribution of the Atchafalaya and Mississippi distributaries to the Texas-Louisiana shelf is similar, but their respective plumes have different structures [*Dinnel and Wiseman Jr.*, 1986]. The Atchafalaya discharges into a very shallow coastal region with a gently sloping shelf. The residence time of Atchafalaya waters is thus enhanced due to the broad shelf impeding the cross-shelf transport of freshwater [*Zhang et al.*, 2012a]. The Mississippi, on the other hand, discharges in a steep narrow shelf region with little interaction with the bottom. It behaves as an intermediate plume [*Yanknovsky and Chapman*, 1997], where the plume interacts with the topography but is still very stratified with the surface front located far offshore of the point where the plume intersects the sea floor. This type of plume will be strongly influenced

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by advection and is more likely to be transported offshore by mesoscale features [*Schiller et al.*, 2011]. The Mississippi discharge east of the river delta may also affect the west side, being transported by wind-driven currents, but little is presently known about this westward transport (and vice versa) of the Mississippi waters around the delta.

[5] In terms of circulation, the Texas-Louisiana shelf may be divided into inner and outer shelf by the 50 m isobath, which is the border where the relative importance of the wind and Loop Current changes [*Nowlin et al.*, 2005]. The main driving force of the inner shelf dynamics in the Texas-Louisiana shelf region is wind, both in terms of the seasonal variability [*Cochrane and Kelly*, 1986; *Cho et al.*, 1998; *Wang et al.*, 1998a] and high-frequency variability [*Zhang et al.*, 2009, 2010, 2012b]. Seasonally, the wind and circulation are clearly divided in two distinct regimes. During nonsummer months, the wind is downwelling favorable (from east), and the shelf waters move downcoast (in the direction that a shelf wave would propagate, directed from the Mississippi River toward the Rio Grande River), transporting the riverine freshwater beyond the Texas-Mexico border. A reversal of wind direction occurs around May or June generating upwelling favorable conditions upcoast and offshore, with a pooling of the Atchafalaya around the river mouth and the convergence of the western Mississippi plume in the Louisiana Bight. These summer conditions only last a few months, and by mid-August the nonsummer wind regime reestablishes. Summer is also characterized by the absence of atmospheric frontal activity, which increases again in fall. The high-frequency band is dominated by land-sea breeze (daily periodicity), especially during the summer, because of the near-resonant condition of the forcing and the near-inertial motions ($\sim$1 day). The shelf currents induced by the breezes represent the strongest nonstorm forced shelf currents, reaching more than 60 cm s^{-1} [*Zhang et al.*, 2009, 2010, 2012b].

[6] The outer shelf is influenced by the mesoscale feature Loop Current (LC) and its associated eddies. LC is a segment of the North Atlantic western boundary current entering the Gulf of Mexico between Yukatán and Cuba and exiting between Florida and Cuba. Instabilities in the LC lead to the formation of large anticyclonic eddies propagating westward [*Sturges and Leben*, 2000]. Both the LC and LC eddies dominate the slope and outer shelf circulation and are known to be an important mechanism of freshwater removal from the northern Gulf of Mexico continental shelf [*Morey et al.*, 2003]. In a recent numerical study, *Schiller et al.*, [2011] examined the impact of the wind-driven and eddy-driven dynamics on the fate of riverine waters and found that the offshore removal by eddies can be as large as the wind-driven shelf transport.

[7] Shelf processes are strongly affected by temporal wind variability, which is difficult to predict beyond several days [*Zhang et al.*, 2012b]. Observations on the required spatial scales and during the best moments to capture events that may explain continental shelf phenomena like hypoxia fluctuations are very difficult to conceive. Numerical models mitigate this limitation. Besides help explaining the processes being studied, ocean simulations may provide indications about the appropriate observational time and space scales. Thus, models may contribute to a better understanding of the complexity of shelf circulations and ecosystems processes [*Bianchi et al.*, 2010]. In coordination with observational studies, ocean modeling has been applied in the major riverine coastal regions, like the Rhine ROFI [e.g., *Souza and Simpson*, 1997], the Columbia river plume [e.g., *Burla et al.*, 2010], the Iberian Buoyant Plume [e.g., *Otero et al.*, 2008], and the Gulf of Maine coastal currents [e.g., *Hetland and Signell*, 2005].

[8] Previous realistic modeling studies of circulation in the Texas-Louisiana region rely on climatological boundary conditions [e.g., *Hetland and DiMarco*, 2008; Wang and Justić, 2009; *Hetland and DiMarco*, 2012]. However, it is known that the use of climatological or analytical boundaries may be limiting model accuracy since important ageostrophic flow components may not be taken into account. In the northern Gulf of Mexico coastal region, averaging observations of the state variables to obtain a monthly climatology, for instance, to be used as boundary condition, leads to low and too smooth density gradients. This happens because the LC shedding cycle is chaotic, not periodic [*Sturges and Leben*, 2000]. The model inflow and outflow of the LC in coastal domains and its influence on the shelf circulation may thus be very unrealistic when using climatological boundaries [*Barth et al.*, 2008]. One solution to properly represent the LC and associated eddies is to use a model domain of the entire Gulf, as done by *Morey et al.* [2003, 2009]. Another solution is to use realistic boundary conditions from large-scale models that assimilate satellite and in situ observed data. The last allows the use of higher resolution shelf domains, contributing to more reliable model results, with a significant improvement in model skill relative to the typical climatological open boundaries [*Barth et al.*, 2008].

[9] The purpose of this work is to infer the improvements to model skill of a coastal model of the Texas-Louisiana continental shelf, given different estimates of the offshore forcing through offline nesting, in comparison with climatological conditions. The climatological modeling configuration we use in this work has been used for several years and is described in detail in *Hetland and DiMarco* [2008, 2012]. It has been applied especially in studies related to the hypoxia problem in the region. One of the conclusions of these studies is the necessity of improving the circulation models to better understand the complexities involving the hypoxia problem, namely in what concerns to large-scale errors which are expected to be reduced by using more accurate offshore ocean variables at the model open boundaries [*Bianchi et al.*, 2010; *Hetland and DiMarco*, 2012]. We expect to improve the skill in nested modeling configurations and will use several offshore large-scale model solutions to provide realistic open boundary data for our coastal domain.

2. Modeling Setup

2.1. Ocean Model

[10] The ocean model used was the Regional Ocean Modeling System (ROMS) [*Shchepetkin and McWilliams*, 2005; *Haidvogel et al.*, 2008], a state-of-the-art free-surface terrain-following primitive equation hydrostatic model, configurable for realistic regional applications. The model domain covers much of the Texas-Louisiana continental shelf (see Figure 1). The grid has 128 by 63 points

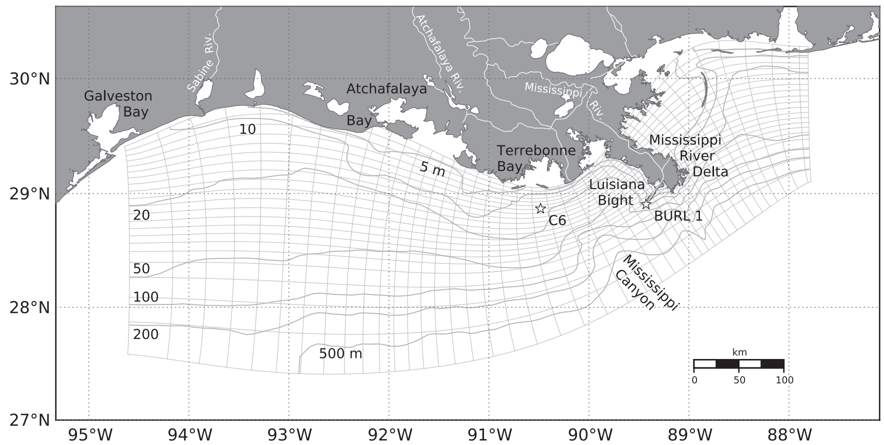

Figure 1. Texas-Louisiana continental shelf model domain. The grid cells are shown each three grid points in both directions, i.e., there are nine cells inside each cell shown here. The main coastal and shelf features and locations are also shown, as well as the Mississippi/Atchafalaya river system.

(along- and cross-shelf direction) with variable resolution, being as low as 20 km around the southwest corner and less than 1 km near the Mississippi river delta (in the cross-shelf direction; in the along-shore direction, the resolution is about 2.4 km there). A realistic bathymetry was used, interpolated from ETOPO, and smoothed to satisfy the maximum topographic-stiffness ratio of 0.2 [*Beckmann and Haidvogel*, 1993]. The minimum depth used was 3 m, and the vertical stretching parameters were configured in order to enhance the vertical resolution at the surface and bottom of 30 vertical levels. The model uses fourth-order horizontal advection of tracers, third-order upwind advection of momentum, and *Mellor and Yamada* [1974] closure with *Galperin* [1988] stability functions. This parameterization has been successfully used over the years in many other works, like *Hetland and DiMarco* [2008, 2012], *Xu et al.* [2011], and *Fennel et al.* [2011].

[11] The model ran with two different configurations: (i) using climatological boundaries and (ii) offline nested into the outputs of a set of Gulf of Mexico operational models, at different boundary information periodicity. The simulation period was 1 January 2004 until the end of 2009.

[12] In the climatological approach (hereinafter CLM), the model boundaries where obtained from profiles of temperature and salinity, spatially and monthly averaged, based on all the World Ocean Atlas (WOA) profiles available for the region. CLM was initialized 1 year before, on 1 January 2003, from rest with zeroed free surface, the first year being a spin-up period. The initial conditions were interpolated in time from the monthly climatology. More details about this climatological configuration can be found in *Hetland and DiMarco* [2008, 2012]. Being a coastal configuration under strong influence of discharge from very big rivers, the use of homogeneous data for initial and boundary conditions may be a reasonable choice. Nevertheless, in order to test the importance of spatial variability of the initial and boundary forcing data, another, more realistic, climatological configuration was conceived (hereinafter CLM_WOA). In these new simulations, the data from initial and boundary conditions were taken from the World Ocean Atlas, spatially heterogeneous (WOA spatial resolution is 1°) and keeping the monthly periodicity. Due to the historical background of CLM, all the analysis in this work rely on CLM, with the exception of model skill for which the results for CLM_WOA are also presented for comparison.

[13] In respect to the nested configuration, data for model initialization and open boundary conditions were taken from different offshore models. A nudging layer of six cells at the three open boundaries (south, east, west) was used to relax the model temperature, salinity, and baroclinic velocities toward the parent models. The nudging time scale used was 8 h at the boundaries with a sinusoidal decay to the interior. In this fully nesting approach, the same nudging time scale was used for the incoming and outgoing information. Radiation conditions [*Marchesiello et al.*, 2003] were used at the boundaries for tracers and baroclinic velocities. Sea surface height and barotropic currents from the parent models were imposed at the boundaries as *Chapman* [1985] and *Flather* [1976] boundary conditions. For a description of the advantages of this nesting approach, see *Barth et al.* [2008]. The parent models have many differences among each other, and with the nested model, like the topography, the grid resolution, the surface forcing, the numerical algorithms, and the river runoff specification. The aim of model nesting is typically to use a lower resolution parent model to force a higher resolution regional configuration, which can benefit from better topography, surface forcing, and numerics.

[14] At the surface, heat and freshwater fluxes are specified using climatological measurements [*da Silva et al.*, 1994]. Tidal forcing was not considered and is known to have a small role in the region [*DiMarco and Reid*, 1998; *Gouillon et al.*, 2010]. Wind forcing is provided with 10 min periodicity from the weather station BURL 1 C-MAN, close to the mouth of the Southwest Pass (89.428°W × 28.905°N, depicted in Figure 1). The horizontally uniform wind is a reasonable approximation, due to the large horizontal spatial scales of the wind field in the study domain [see *Wang et al.*, 1998a]. The use of real wind and with very high sampling rate is an advantage since it includes the wind peaks and the sea breeze. In particular, the breeze has great importance on the surface heat budget and shelf currents [*Zhang et al.*,

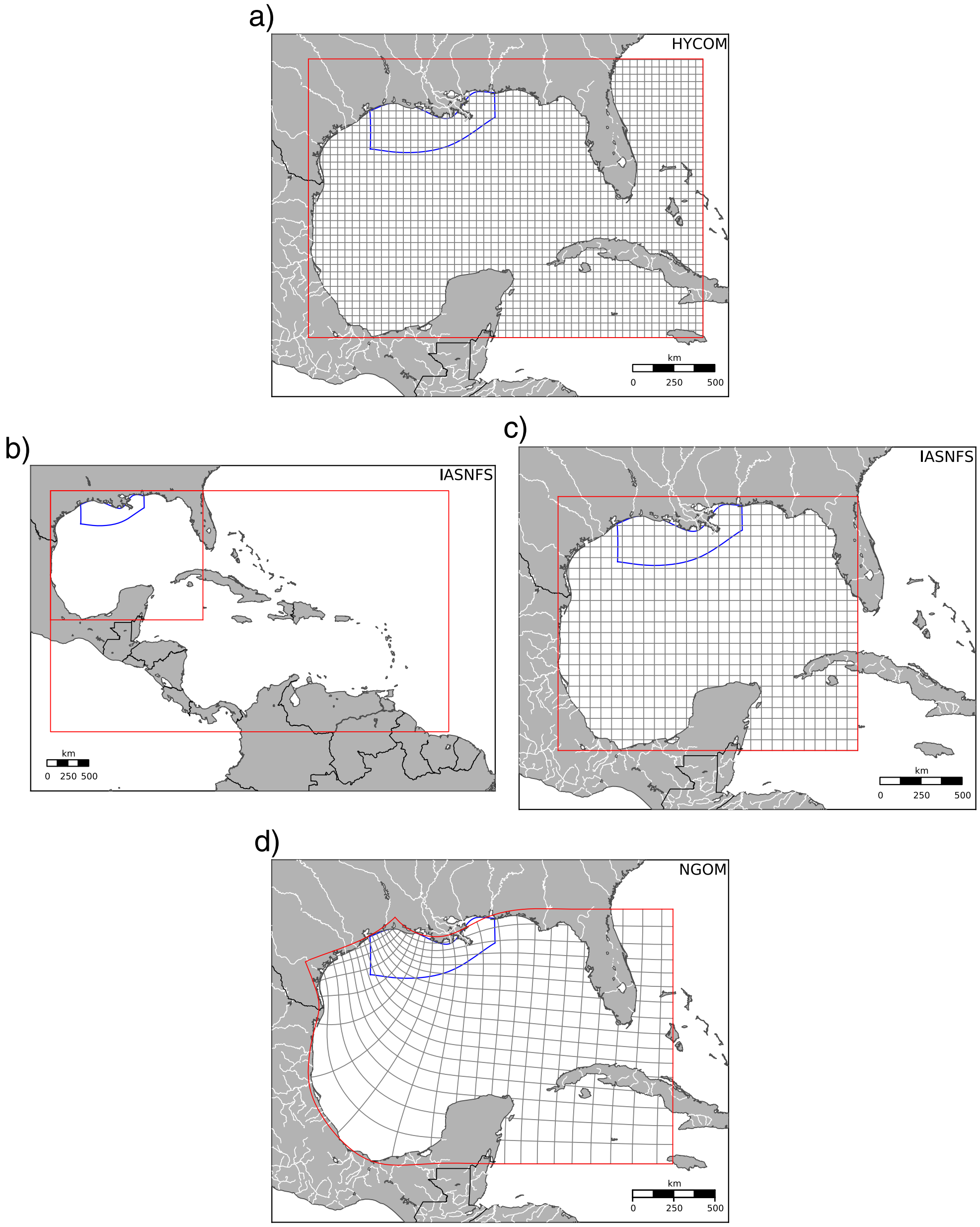

Figure 2. Numerical domains of the offshore parent models used to provide realistic boundary conditions: (a) HYCOM, (b) IASNFS, (c) IASNFS zoom, (d) NGOM . Cells are shown each 10 grid points in both directions. IASNFS is zoomed to the same geographical limits of HYCOM and NGOM in order to provide a visual idea of the different resolution of the models.

2009, 2010]. Obtaining non-uniform wind data at enough frequency to fairly reproduce the breeze would require a local area atmospheric model.

[15] The two major riverine sources of the region (and of Gulf of Mexico), the rivers Mississippi and Atchafalaya, were specified using daily averaged measurements at the Tarbert Landing site (U.S. Army Corps of Engineers). The Mississippi and Atchafalaya flow ratio of the Tarbert Landing streamflow is set at 2/3 for the Mississippi and 1/3 for the Atchafalaya, the target ratio maintained by the U.S. Army Corps of Engineers. River water temperature is set as equal to the surface air temperature from the *da Silva et al.* [1994] climatology for the region.

2.2. Offshore Parent Models

[16] The shelf model was nested within three different parent models: HYCOM, IASNFS, and NGOM, with output frequency of 24 h, 6 h, and 3 h, respectively. Each of these models was used to provide boundary data with 24 h periodicity (hereinafter HYCOM·24, IASNFS·24, and NGOM·24) and at their higher frequency output, in the case of IASNFS and NGOM (IASNFS·06 and NGOM·03). Thus, we end up with five different boundary data sets. The domains of these models are illustrated in Figure 2.

[17] The Gulf of Mexico operational HYCOM model (HYbrid Coordinate Ocean Model, *Wallcraft et al.* [2009],

http://www.hycom.org) is a dynamic generalized vertical coordinate ocean model. The model domain is depicted in Figure 2a. The horizontal resolution is about 4 km, and vertically 20 surfaces are used. HYCOM possesses the advantages of the different vertical discretizations to simulate from shallow coastal features to large-scale open-ocean circulation. The hybrid vertical discretization dynamic transitions between the different coordinates: isopycnal in the open, stratified ocean; terrain-following in coastal regions; and constant z level coordinates in unstratified areas (like the surface mixed layer). The HYCOM nowcast/forecast system runs in real time at the Naval Oceanographic Office (NAVOCEANO). Surface atmospheric forcing is taken from the Navy Operational Global Atmospheric Prediction System (NOGAPS). HYCOM assimilates data from several sources, including satellite along-track altimetry observations, satellite and in situ sea surface temperature, vertical salinity and temperature profiles from XBTs, ARGO, and moored buoys. Assimilations are done with the Navy Coupled Ocean Data Assimilation system (NCODA, *Cummings* [2005]). The gulf of Mexico HYCOM implementation is nested in the Atlantic scale 1/12° HYCOM model. The model outputs are available in an OPeNDAP server as daily snapshots at standard Levitus depth levels.

[18] IASNFS—Intra Americas Sea Nowcast Forecast System—is an operational nowast/forecast model covering Central America and Gulf of Mexico (Figure 2b) [*Ko et al.*, 2003, 2008, *Chassignet et al.*, 2005]. It is operated by the Naval Research Laboratory (NRL) Oceanography Division founded by NASA. The horizontal resolution is about 6 km, and vertically it has 41 hybrid sigma-z levels. IASNFS boundary data are provided by NRL 1/8° Global NCOM model, operated daily. The model assimilates vertical profiles of temperature and salinity generated by MODAS (Modular Ocean Data Assimilation System) and sea surface temperature and satellite altimetry. Surface fluxes are also provided by NOGAPS. Model outputs are available via OPeNDAP at 38 constant z levels.

[19] NGOM is an operational system based on the Princeton Dyanalysis Ocean Model [*Blaha et al.*, 2000; *Mellor et al.*, 2002; *Patchen and Blaha*, 2002] providing forecasts for the Gulf of Mexico at the NAVOCEANO Major Shared Resource Center. It provides nowcasts/forecasts and assimilates satellite sea surface height, surface temperatures, and derived salinity. Surface atmospheric data used by NGOM are provided by the Navy's Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS). The vertical discretization is done with generalized sigma-coordinate levels, and the horizontal resolution is variable. The domain covers the Gulf of Mexico using a curvilinear grid (Figure 2d) with increased resolution in the northwest of the gulf. Horizontal resolution in the east-west direction (predominantly) ranges from 2.7 to 40 km and in the north-south direction ranges from 1.7 to about 25 km. Model results are available by OPeNDAP at 37 sigma levels.

2.3. Observations

[20] The data used in this study for model skill assessment were collected in the context of two observational programs: SEAMAP and MCH. SEAMAP—Southeast Area Monitoring and Assessment Program—is a program administrated by the Gulf States Marine Fisheries Commission for collection, management, and dissemination of fisheries-related scientific data. One of the operational components of the program is dedicated to the Gulf of Mexico and started back in 1981. Its regular surveys collect fishery and environmental data, including temperature and salinity vertical profiles along the Texas-Louisiana continental shelf. The SEAMAP data used here were collected during May, June, and July 2004 to 2008. Each observational campaign lasted 1–2 months and summed a total of 605 valid profiles within the model domain during the whole period, observed during a total of 235 days.

[21] The MCH project—Mechanisms Controlling Hypoxia—included hydrographic data collection extending from April to end of August between 2004 and 2008, except 2006. Twelve cruises with a duration of 2 to 6 days collected inner shelf vertical profiles of temperature, salinity, and dissolved oxygen. For more details on the MCH observational sessions and techniques, see *DiMarco et al.* [2010]. A total of 1128 valid profiles were done inside the model domain and used in the present study during 68 days.

[22] The first four columns of Table 1 summarize the MCH and SEAMAP survey periods together with the number of profiles per observational session. Almost all MCH profiles were sampled in sites with depth lower than 50 m (near 99%). For SEAMAP, about 70% of the profiles had depth lower than 50 m, and about 30% had depths between 50 and 100 m. The higher concentration of MCH profiles was around the isobath 20 m (Figure 3a), while SEAMAP profile locations were roughly uniform over the shelf (Figure 3b).

3. Results

[23] The model assessment is primarily focused on the ability of the model to accurately reproduce salinity fields. This is because the salinity field requires accurate simulation of lateral transport of freshwater from the two major rivers across the shelf; lateral advection is a potential source of numerical errors in simulations of river plumes [e.g., *Hetland and Signell*, 2005]. Both numerical simulations and observations show strong along- and cross-shelf gradients in salinity. Temperature, on the other hand, is primarily a vertical process—lateral gradients of sea surface temperature are relatively weak across the shelf, particularly in summertime. Currents have been shown [*Hetland and DiMarco*, 2012] to have smaller skill because local variations in topography and small scale circulation features dominate the signal. Salinity at a point on the shelf, on the other hand, integrates a variety of advective and mixing processes and is thus less sensitive to local details of flow and topography [*Hetland*, 2010]. Sea level is primarily influenced by barotropic processes and is well reproduced in numerical simulations that do not include prognostic density variations. Thus, we believe comparisons between simulated and observed salinity fields is the best way to assess broad, shelf-scale circulation over the Texas-Louisiana shelf.

[24] Salinity is the major contributor for spatial stratification differences on the Texas-Louisiana shelf, as a consequence of the big riverine discharges and high evaporation and precipitation in the region. On average, the evaporation over the shelf is equivalent to about 25% of the river inputs, and evaporation is about twice as large as the

Table 1. MCH and SEAMAP Observational Sessions Periods and Number of Profiles Inside the Numerical Domain Together with the Salinity Model Skill of the Nesting Parent Models, ROMS with Climatological Homogeneous and Spatially Variable Boundary Conditions (CLM and CLM_WOA), and ROMS Nested in the Parent Models[a]

				Parent Models							ROMS Nested				
Obs.	Date	N. Days	N. Prof.	HYCOM·24	IASNFS·24	IASNFS·06	NGOM·24	NGOM·03	CLM	CLM_WOA	HYCOM·24	IASNFS·24	IASNFS·06	NGOM·24	NGOM·03
	02 Apr 2004	6	58	0.07	0.31	0.33			0.14	0.45	0.31	**0.57**	**0.59**		
	26 Jun 2004	6	60	0.10	0.29	0.28			0.34	0.58	**0.65**	**0.66**	**0.70**		
	21 Aug 2004	6	63	–0.05	0.24	0.19			0.19	0.40	0.43	**0.71**	**0.70**		
	23 Mar 2005	7	104	0.21	**0.44**	**0.53**			**0.48**	**0.45**	**0.49**	**0.46**	**0.46**		
	20 May 2005	7	100	0.09	–0.01	0.16			0.13	0.31	**0.46**	**0.45**	**0.38**		
	08 Jul 2005	6	142	0.45	0.36	0.54			**0.71**	**0.67**	**0.60**	**0.67**	**0.64**		
MCH	18 Aug 2005	7	231	0.12	**0.76**	**0.77**			**0.74**	**0.74**	**0.68**	**0.80**	**0.65**		
	23 Mar 2007	7	122	0.21	–0.47	–0.44	**0.67**	**0.63**	**0.64**	0.44	**0.61**	**0.73**	**0.74**	**0.62**	**0.68**
	17 Jul 2007	4	60	–0.28	0.10	0.23	0.38	0.37	**0.50**	**0.63**	**0.51**	**0.54**	**0.58**	**0.62**	**0.55**
	06 Sep 2007	5	74	*–0.52*	*–0.49*	*–0.64*	*–2.55*	*–2.57*	*–1.96*	*–0.71*	*–1.85*	*–1.52*	*–0.50*	*–0.47*	*–0.98*
	16 Apr 2008	3	43	0.29	0.33	0.20	**0.69**	**0.71**	0.55	0.47	0.46	0.50	0.47	0.56	0.53
	17 Jul 2008	4	71	–0.11	0.50	0.52	0.54	0.50	0.24	0.46	**0.65**	**0.62**	0.58	**0.74**	**0.74**
	all dates	68	1128	0.12	0.22	0.26	**0.52**	**0.50**	0.42	0.48	**0.52**	**0.58**	**0.57**	**0.62**	**0.62**
	14 May 2004	62	41	0.03	0.16	0.16			0.32	**0.58**	0.48	**0.55**	**0.63**		
	15 Jun 2005	46	22	–0.23	–0.02	0.11			–1.06	0.06	–0.06	0.17	**0.23**		
SEAMAP	14 Jun 2006	33	265	–0.56	–2.74	–2.44	**0.61**	**0.60**	–0.38	0.26	–0.13	–0.80	–0.85	**0.52**	**0.54**
	07 Jun 2007	58	48	–0.39	–0.02	0.16	0.08	0.08	–0.12	**0.33**	0.25	0.02	0.10	0.23	0.19
	11 Jun 2008	36	229	–0.21	0.37	**0.41**	**0.40**	**0.42**	0.22	0.33	**0.46**	0.35	0.37	0.30	**0.47**
	all dates	235	605	–0.35	–0.87	–0.73	**0.47**	**0.48**	–0.04	0.31	0.22	–0.09	–0.09	**0.39**	**0.48**

[a]In bold are shown the positive skills between the maximum skill obtained per observational session and 20% less than that value. The skills corresponding to the MCH session of 6 September 2008 are all negative and shown in italic.

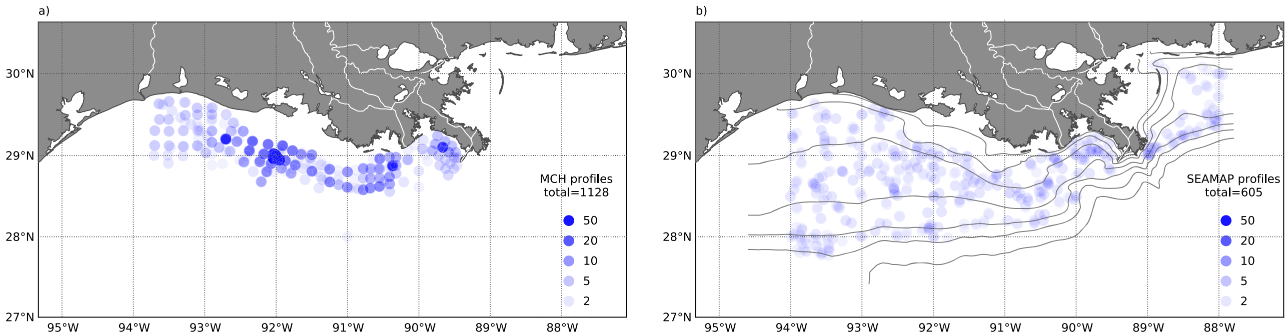

Figure 3. (a) MCH and (b) SEAMAP survey profiles locations and density.

precipitation. During the summer months, when the discharge is minimum and the precipitation and evaporation are maximum, these three quantities may have similar value [*Dinnel and Wiseman Jr.*, 1986; *Etter et al.*, 2004].

3.1. Seasonal Overview

[25] Figure 4 shows the monthly mean sea surface salinity and wind forcing for the year 2008 from the IASNFS·24 run. In the summer months (June–August), winds are weak and upwelling favorable, and freshwater tends to pool on the shelf and move offshore, thereby intensifying stratification over the shelf. 2008 is a flood year; the Mississippi River discharge has a peak value of $\sim$40,000 m^3 s^{-1}, 30% larger than the average peak value of $\sim$30,000 m^3 s^{-1}. Therefore, the river plume in 2008 is bigger than average and extends further offshore, as there is a correlation between the plume area and the freshwater discharge. In the nonsummer months (September–May), the winds intensify and reverse to downwelling favorable, which enhances downcoast flow of freshwater and causes a narrow freshwater belt hugging the coastline. The stratification on the midshelf created in summer is reduced in winter due to the efficient downcoast transport of freshwater within a strong, narrow coastal current and due to frequent passages of atmospheric fronts that mix the water column. These results are consistent with previous results [*Cochrane and Kelly*, 1986; *Cho et al.*, 1998; *Nowlin et al.*, 2005], which show the inner shelf circulation, within the 50 m isobath, to be mainly wind-driven.

[26] Figure 4 shows an example from 1 year with the IASNFS·24 nesting parameterization. For other years, the model results display similar qualitative patterns, with interannual variability that is modulated by changes in prevailing winds and the magnitude of the freshwater discharge. The seasonal oceanic features described above are also reproduced in the simulations with other parent models and with climatological boundary conditions. To illustrate this, Figure 5 shows the surface salinity of the climatological and nested configurations (nested results overlaid on the parent model salinity) on 19 July 2008, 00 h, during the last MCH observational session (17 to 20 July 2008). The colored dots indicate the observed surface salinity. All solutions qualitatively reproduce the summer upwelling conditions with weak eastward wind and the Mississippi and Atchafalaya River plumes pooling over the shelf. The importance of the offshore circulation features interacting with the freshwater over the shelf is clear; especially in the IASNFS·06 and IASNFS·24 results, low salinity filaments created by interaction with the loop current extend offshore and remove freshwater from the shelf. The importance of realistic freshwater conditions imposed in the east and west boundaries is also evident, as in all cases the broader plume exceeds the boundaries of the small child domain. With a better representation of the broader plume, outside of the child model domain, the nested models are better able to reproduce the spatial variability of surface salinity associated with the Atchafalaya river plume on the mid shelf. The importance of this is highlighted further in the next section.

3.2. Export of Freshwater From the Shelf

[27] Two major differences between the run with climatological open boundary conditions and those with realistic boundaries are that the latter allow freshwater to reenter the region from the boundaries and offshore circulation patterns can enhance export of freshwater off the shelf. CLM allows freshwater to enter the domain at timescales longer than the relaxation timescale but only slightly freshwater associated with the climatology, which may create a high salinity bias. On the other hand, CLM does not contain information about offshore mesoscale eddies, which tend to enhance offshore transport of plume waters, which may create a fresh bias in CLM. Wind-driven shelf currents may be an important mechanism of freshwater input through the shelf boundaries, mainly upcoast freshwater transports through the western boundary, and offshore eddies may occasionally transport freshwater back to the shelf through the southern boundary. On the other hand, because climatological boundaries are based on averages of spatially varying features, the simulations with realistic boundaries are expected to have stronger interaction with the offshore mesoscale circulation (Loop Current and eddies) and thus enhanced exchange of freshwater in boundary regions under the influence of these features. The reduction in offshore transport due to interaction with Loop Current eddies may decrease the export of freshwater and cause a fresh bias in the climatological boundary condition runs.

[28] Figure 6 shows the net freshwater flux, U_f, normal to the boundary entering or leaving the model domain though the western, southern, and eastern open boundaries, for the several model parameterizations. The freshwater flux is defined as the integral of the velocity, u_n, normal to the

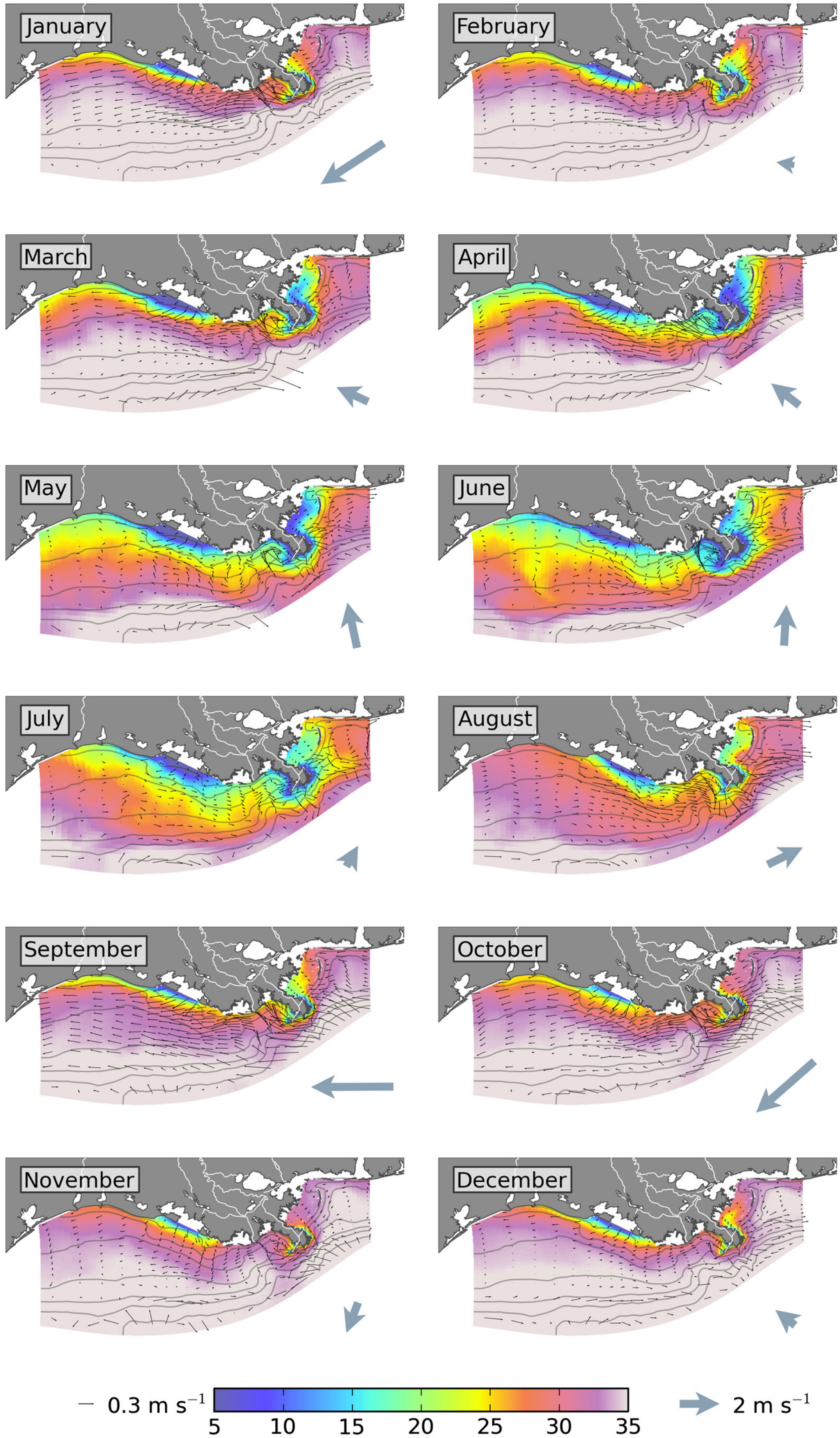

Figure 4. Monthly averaged sea surface salinity, surface currents, and wind of the IASNFS·24 simulation for 2008.

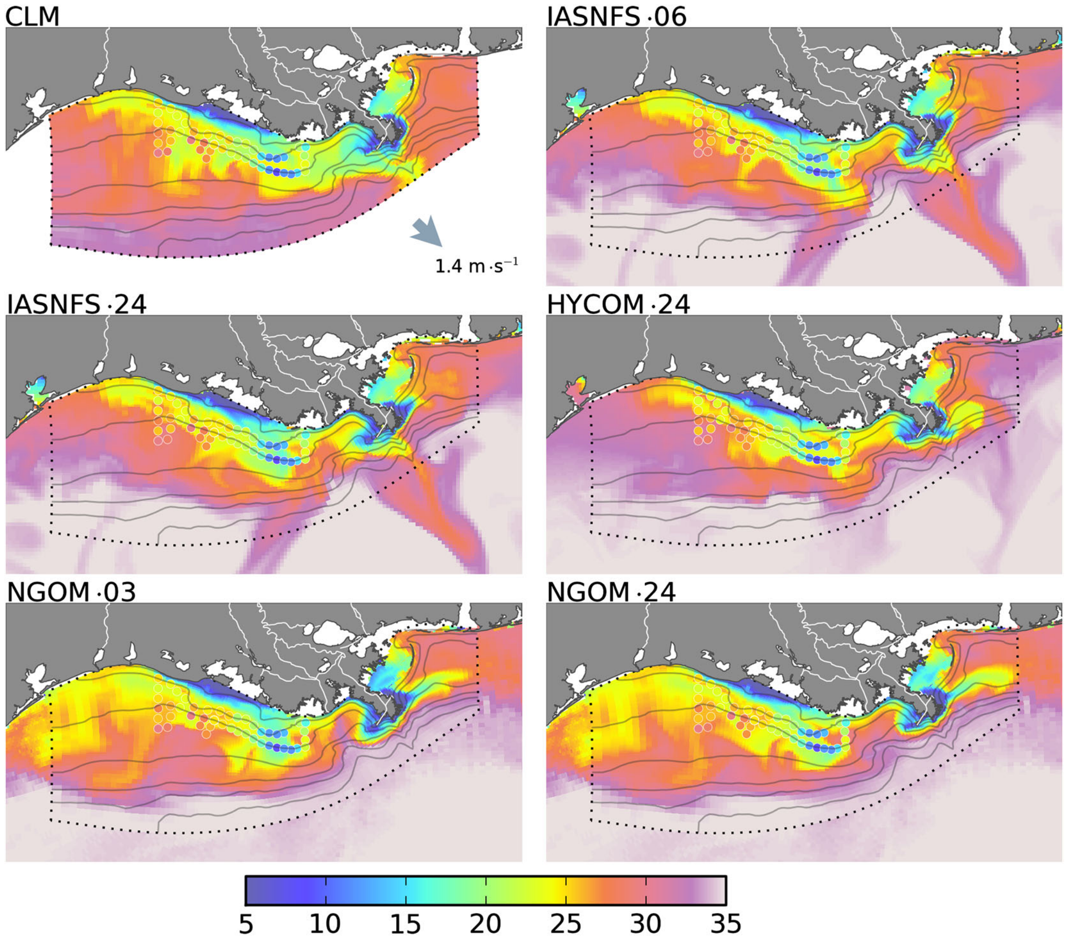

Figure 5. Surface salinity of the several model parameterizations on 19 July 2008, 00 h, in the middle of the last MCH survey (17 to 20 July 2008). The arrow in the bottom right corner of the CLM plot represents the averaged wind during the previous week. The colored dots compare the modeled surface salinity with the observed one during the 4 days of the survey.

boundary times the freshwater anomaly, integrated over the entire boundary, *BRY*,

$$U_f = \iint\limits_{BRY} \frac{S_0 - S}{S_0} u_n \, \mathrm{d}A_{BRY}. \tag{1}$$

The reference salinity, S_0, used in the calculation of the freshwater flux shown was 36.0. A range of values, from 35 to 36.5, was also used without significant qualitative differences. The value 36.0 was chosen based on a separate set of numerical experiments with riverine input of a passive tracer [*Zhang et al.*, 2012a]. In the western boundary, the nested runs show comparable transports and differ from CLM, especially during the summer. CLM has negative freshwater flux during almost the entire simulation (i.e., out of the domain), while the nested results show the typical inversion of flux during the summer with the inflow of shelf freshwater into the model region. At the southern boundary, the differences between the climatological and realistic boundaries simulations are much higher. CLM maintains positive freshwater flux entering the shelf, while in the nested simulations, freshwater is generally removed from the domain. There is net onshore flow of relatively saline water (but still $S < 36.0$) in CLM along the southern boundary that must be balanced by either localized export of much fresher water or an increased downcoast flow of freshwater out of the western boundary.

[29] The freshwater flux through the eastern boundary shows large differences between the several simulations. Similarities exist only among simulation with the same parent model (same model but different boundary data periodicity, i.e., between NGOM·03 and NGOM·24, and between IASNFS·06 and IASNFS·24). Since the eastern boundary is near the Mississippi delta, the freshwater is influenced by the way rivers are implemented in each parent model. For instance, the model nested in HYCOM has positive freshwater flux during most of the simulation period, while in NGOM·03 and NGOM·24, the flux is essentially negative. On the other hand, CLM, IASNFS·06 and IASNFS·24 show no regular freshwater flux pattern in the eastern boundary.

3.3. Model Skill Assessment

[30] The quantitative evaluation of the model performance is based on the model skill, defined as

$$\text{skill} = 1 - \frac{\sum (o_i - m_i)^2}{\sum (o_i - c_i)^2} \tag{2}$$

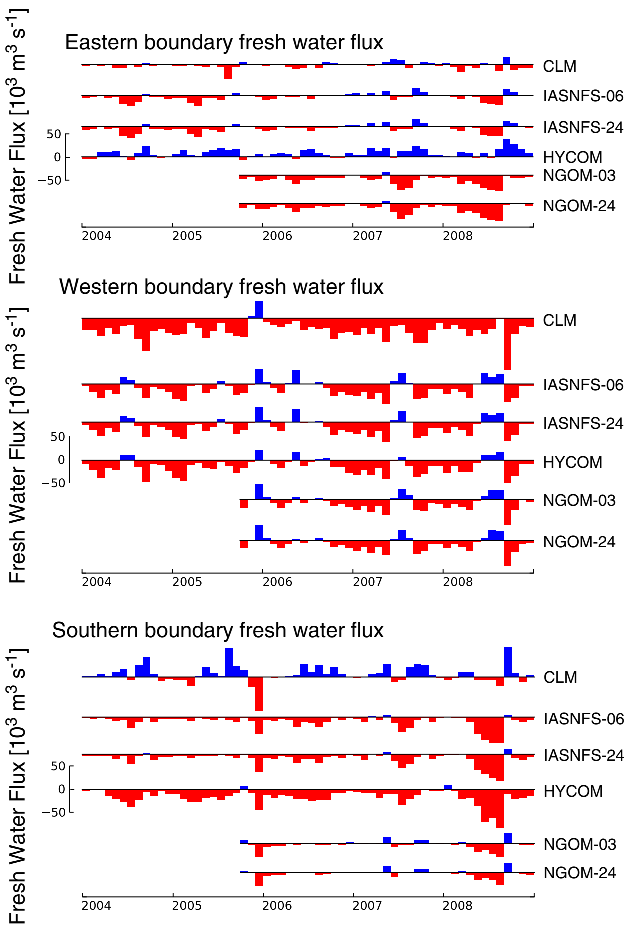

Figure 6. Monthly averaged freshwater flux across the model open boundaries (positive values mean entering the model domain). The freshwater reference salinity used was 36.0.

where o_i are the observations, m_i the model results at the same locations and times, c_i is the climatological data, and i is an index that represents each measurement point [*Bogden et al.*, 1996; *Hetland*, 2006]. The climatological data were calculated as monthly averages from all the available profiles collected in the past decades in the northern Gulf of Mexico and are laterally uniform, i.e., there is only one profile per month, consisting of the same data used for the initial and boundary conditions of the climatological CLM runs.

[31] The numerator is the variance of the model error, and the denominator is the variance of data relative to climatology. If the model error is zero, i.e., the model reproduces the observations with full accuracy, the skill will be 1. If the model error is equal to the variance in the observations, the model skill will be 0, and in such cases it makes no sense to use numerical model results for its original purpose. In the extreme, the skill can be negative (model error variance is larger than data variance) indicating the model actively disagrees with observations. Even a perfect model may actually have skill lower than 1 because of observational errors and because of random variability (e.g., turbulence or small scale internal waves) unresolved by the model. Nevertheless, in general, a positive skill indicates the model provides an improved representation of the observations relative to the climatology [*Hetland*, 2006].

[32] The spatial difference in the distribution of the profiles of MCH and SEAMAP (Figure 3) provides valuable information to assess the importance of the offshore circulation and the impact of model nesting on the continental shelf and slope. Table 1 summarizes the skill of MCH and SEAMAP for several observational sessions. The simulations with climatological boundary conditions are indicated in the columns CLM (homogeneous conditions) and CLM_WOA (spatially variable initial and boundary data from WOA); Parent Models and ROMS Nested represent the skill of the offshore models and the results of nested simulations, respectively. Positive skills between the maximum skill for the survey (among all the skills calculated, 12 per table line) and 20% less than that value are shown in bold. It is clear that the nested configurations (right side, ROMS Nested) have more marked simulations, demonstrating the benefit of model nesting for this shelf and slope model implementation.

[33] Considering the skill values for the MCH cruises (consisting of profiles in the inner and middle shelf), it is evident that almost all the nested simulation skills are above the CLM values, specially the results referent to the nesting with IASNFS (·24 and ·06). This is noteworthy, as it was expected that the inner shelf is insensitive to deep Gulf circulation patterns. The parent models have lower skill than the climatological simulation CLM, indicating these models are not good to represent shelf salinity. This is however not true for the two NGOM models (·24 and ·03), which in general have comparable skill to the results of the nested solution.

[34] In the first 2 years of MCH observations, all the nested model skills are in general higher than 0.5, indicating the model ability to reproduce more than half of the observed salinity variance, in addition to the climatological one. Results for the second MCH group of observational sessions (2007 and 2008) also show nested models skills in general higher than 0.5, with the exception of the very strange skills associated with the last survey of 2007, where all skills are negative. This may indicate some extreme event of frontal activity not correctly taken into account by none of the offshore models. It is known that storm events may have sudden impacts on the northern Gulf of Mexico shelf circulation and break the stratification during some days. These events become frequent by the end of August [*Wiseman et al.*, 1997]. The more realistic climatological results CLM_WOA have comparable skills to CLM with a small overall increase from 0.42 to 0.48 (line "all dates" in Table 1).

[35] The skills relative to the SEAMAP observations are much smaller than the MCH ones, being in general lower than 0.5. As in the MCH case, the general trend is for higher skill in the nested simulations, especially with NGOM and IASNFS boundaries. It is important to note the very low skill of the CLM run. The SEAMAP observations are more widely sampled through the entire shelf (Figure 3), with about 30% of the profiles outside the 50 m isobath, while for MCH this value is only about 1%. The skill scores associated with the SEAMAP cruises are thus more sensitive to model results in the outer shelf, unlike the MCH cases. Since the climatological model has no real time informa-

tion at the boundaries, realistic interaction of the offshore water masses with the shelf domain does not exist. The mesoscale features (the LC and LC eddies) directly impact in the calculated model skill with the SEAMAP observations. The climatological CLM model has moderate skill in the inner and middle shelf, but this accuracy decreased in the outer shelf. For instance, the second SEAMAP observational session, which started on 15 June 2005 and lasted 46 days, shows climatological model skill lower than –1. In between this SEAMAP period, there was one MCH survey (8 to 13 July 2005) with climatological (and nested) model skill around 0.7. Results of nesting with the several offshore models show very different skill for the 2006 SEAMAP observations. ROMS model resolution is quite coarse in the outer shelf, so that different representations of the offshore large-scale circulation by the parent models, as well as small-scale processes in the nested simulations, may be affecting the skill calculated, which is based on instantaneously measured data. CLM_WOA skills for SEAMAP are better than CLM. Considering all the observations (line "all dates"), CLM_WOA skill is actually only lower than skills for NGOM (parent and nested).

[36] One important result from the comparison with SEAMP observations is that in spite of having lower skill than MCH, the skill of the nested models is in general much higher than the skill of the climatological CLM boundaries run. This indicates that nesting improves the model accuracy on the outer shelf and slope. It is interesting that CLM_WOA also shows high skills, in some cases, higher than some nested models. However, since large variability exists in the SEAMAP skills of the nested models, what is important are the big average skill differences. The different results, for both MCH and SEAMAP, of the several nesting approaches should not be seen as negative. Different models are supposed to give a different answer to external forcings and are also supposed to be more parameterized to answer a certain problem. It is even possible to obtain worse skill results with more complex models, i.e., a model can have high accuracy dealing with some kind of events and fail to properly simulate others.

[37] For comparison, skill was also calculated for the temperature profiles, listed in Table 2. In contrast to the skill scores for salinity, nested model results of the temperature field do not show a marked improvement. Also, when comparing to the SEAMAP hydrographic cruises, the parent models tend to do better—particularly the IASNFS models. We attribute this to the fact that the SEAMAP measurements cover a much broader and deeper portion of the shelf as compared to the MCH measurements, which are predominantly taken between the 10 and 20 m water depth. The effect of the boundary conditions is minimized within the 50 m isobath, where the flow is influenced mainly by freshwater discharge and local winds [*Nowlin et al.*, 2005].

3.4. Wind and River Perturbation Experiment

[38] A set of simulations was done to access the model response to perturbations in the forcings. Four tests were done changing the wind forcing and river discharge by 5%. The configuration used was IASNFS·24 from January 2008 until the end of February 2009. The objective was to access the model noise for the winter and summer seasons. The noise of each simulation was calculated for surface salinity at each horizontal grid point in the model domain and is defined as

$$\mathrm{noise}_i = \frac{\mathrm{std}(s_i - s_{\mathrm{EM}})}{\mathrm{std}(s_{\mathrm{EM}})} \tag{3}$$

where s_i is the surface salinity of each simulation and s_{EM} is the ensemble mean. Given that the perturbation is small, we expect a small noise if the system responds in a linear way. If the noise is large, it implies inherent nonlinearities in the system response. The results are shown in panels of Figure 7. The first four rows show the results of the four experiments, and the bottom row shows the noise for all runs defined as the average of the four noises. The first column shows the noise calculation in summer (June, July, and August 2008), and the second column shows the noise calculated using only winter salinity (December 2008 and January and February 2009). In all cases, the noise is much higher in the summer as compared to that in winter, indicating that the system behaves differently in different seasons and that there is more variability in the surface salinity in summer due to nonlinear processes.

3.5. Nested Models Comparison

[39] The differences among the nested models were quantified by the deviation of salinity relatively to the average salinity of the five different nested simulations:

$$\mathrm{noise} = \frac{s - s_{\mathrm{EM}}}{\mathrm{std}(s_{\mathrm{EM}})} \tag{4}$$

[40] This calculation was done with time series from each nested model run of surface salinity at the inner shelf south of Terrebonne Bay (LUMCON mooring location C6, 90.483°W × 28.867°N, indicated in Figure 1) and with time series of the domain averaged surface salinity. s_{EM} is the ensemble average time series, and its standard deviation is 3.2 and 2.5 g kg^{-1} for the C6 site and whole domain, respectively. The result is shown in Figure 8. While the domain-wide deviations in surface salinity between model runs are less than 50% of the standard deviation of the ensemble of runs, the differences in model runs at a point are often higher than 100%, particularly in the summer, and can be over 200%.

4. Discussion

[41] All of the parent and nested models qualitatively reproduce the known seasonal circulation patterns. Also, all of the parent and nested models generally exhibit positive skill at reproducing observed summertime salinity patterns. The most skillful models are the various nested models, indicating that nesting improves both the shelf model using climatological boundary conditions and the skill of the parent models in the same region. This is interesting, given that we did not modify the forcing for the nested model to match that of the parent models. The river discharges and surface heat and momentum fluxes are identical in all of the nested models. In fact, the nested model uses horizontally uniform winds, based on the BURL 1 meteorological station. The original motivation for this choice was that high temporal resolution of the wind field was more important than spatial gradients; the horizontal spatial scales of the regional winds are estimated to be about 400 km [*Wang et al.*, 1998b]. Using

Table 2. Same as Table 1 But With Model Skill Based on Temperature

				Parent Models							ROMS Nested				
Obs.	Date	N. Days	N. Prof.	HYCOM·24	IASNFS·24	IASNFS·06	NGOM·24	NGOM·03	CLM	CLM_WOA	HYCOM·24	IASNFS·24	IASNFS·06	NGOM·24	NGOM·03
MCH	02 Apr 2004	6	58	0.38	**0.65**	**0.66**			**0.61**	–0.07	0.24	0.48	0.38		
	26 Jun 2004	6	60	0.51	0.46	0.46			0.50	**0.58**	0.21	**0.70**	**0.67**		
	21 Aug 2004	6	63	–0.26	0.05	0.09			–0.14	0.04	**0.44**	0.40	**0.53**		
	23 Mar 2005	7	104	**0.54**	**0.62**	**0.63**			**0.60**	**0.60**	**0.59**	**0.61**	**0.60**		
	20 May 2005	7	100	0.34	0.14	0.14			0.43	**0.50**	**0.51**	**0.50**	**0.55**		
	08 Jul 2005	6	142	0.60	**0.80**	**0.80**			0.40	0.42	0.49	0.45	0.43		
	18 Aug 2005	7	231	0.61	**0.73**	**0.74**			**0.66**	**0.73**	**0.82**	**0.74**	0.61		
	23 Mar 2007	7	122	**0.82**	**0.82**	**0.82**	**0.73**	**0.73**	**0.76**	**0.76**	**0.68**	**0.79**	**0.80**	**0.69**	**0.72**
	17 Jul 2007	4	60	*–1.15*	*–0.47*	*–0.28*	*–0.99*	*–0.96*	*–0.41*	*–1.76*	*–0.27*	*–0.93*	*–1.40*	*–4.06*	*–4.20*
	06 Sep 2007	5	74	**0.88**	**0.88**	**0.89**	0.12	0.11	**0.72**	**0.76**	**0.75**	**0.76**	**0.78**	0.31	–0.06
	16 Apr 2008	3	43	0.49	**0.87**	**0.89**	0.43	0.45	0.39	0.45	0.39	0.36	0.36	0.39	0.41
	17 Jul 2008	4	71	–1.54	–0.59	–0.60	0.03	0.05	**0.41**	0.16	**0.36**	0.03	0.15	–1.57	–1.31
	all dates	68	1128	0.41	**0.52**	**0.53**	0.26	0.26	**0.54**	**0.54**	**0.59**	**0.58**	**0.56**	–0.20	–0.26
SEAMAP	14 May 2004	62	41	–0.36	**0.39**	**0.41**			0.06	0.31	**0.40**	**0.41**	**0.44**		
	15 Jun 2005	46	22	–0.29	**0.55**	**0.56**			0.49	0.46	0.33	**0.63**	**0.56**		
	14 Jun 2006	33	265	–0.44	**0.41**	**0.39**	–2.61	–2.58	0.18	–0.33	0.29	0.08	0.11	–3.45	–3.59
	07 Jun 2007	58	48	–0.30	**0.07**	**0.07**	–0.80	–0.76	–0.16	–1.90	–0.36	–0.98	–0.89	–3.76	–3.76
	11 Jun 2008	36	229	–0.37	**0.41**	**0.41**	–0.26	–0.26	–0.08	–0.19	0.01	0.12	0.09	–1.21	–1.19
	all dates	235	605	–0.39	**0.40**	**0.40**	–1.45	–1.43	0.07	–0.24	0.16	0.12	0.12	–2.42	–2.48

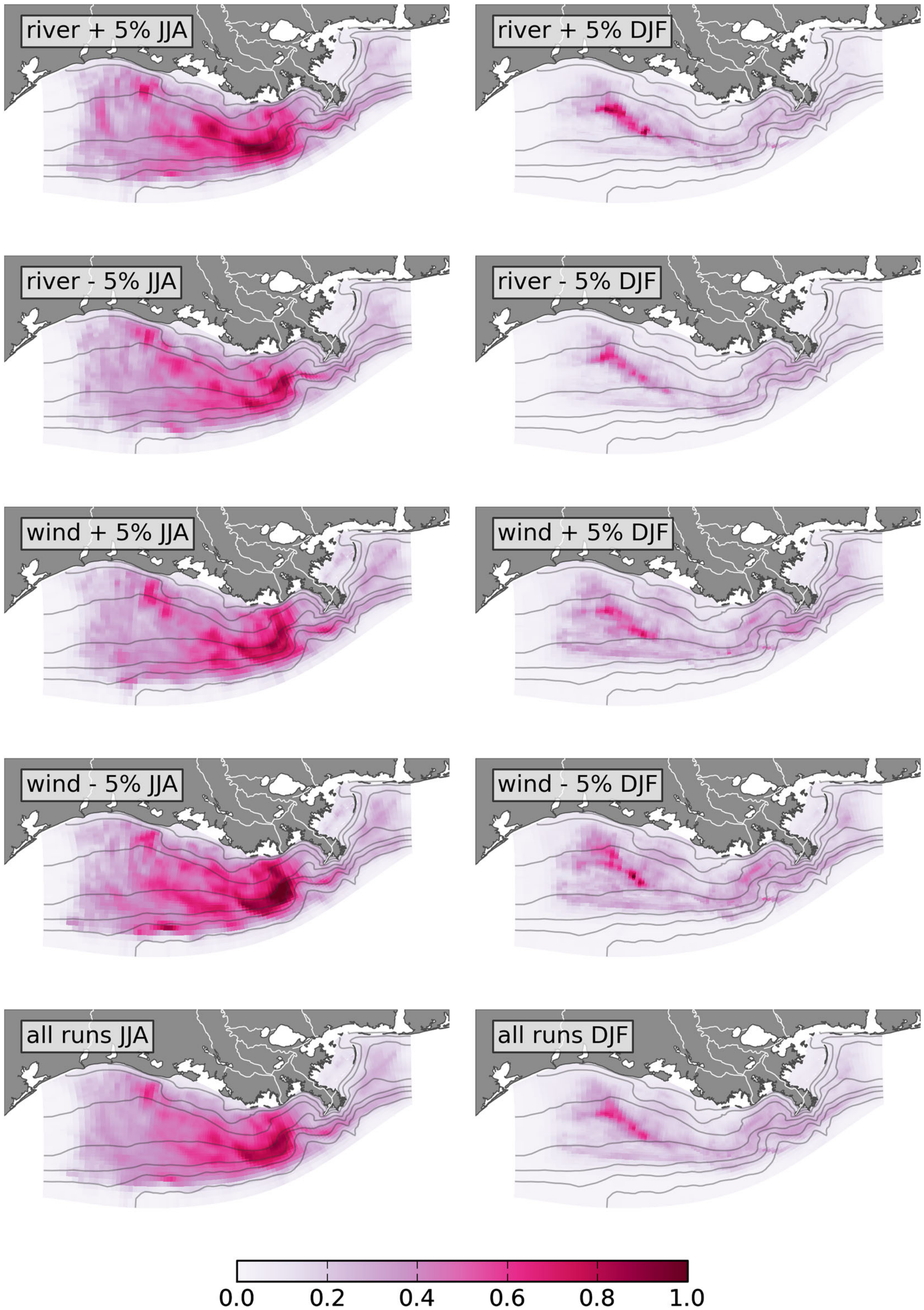

Figure 7. Model surface salinity noise of IASNFS·24 run, perturbed by increasing and decreasing the wind forcing and river discharge 5%. Left panel shows the results for June, July, and August 2008; at right are shown the results for December 2008 and January and February 2009.

different forcing in the parent and nested models did not degrade the nested model results; to the contrary, the nested results had the highest skill. Thus, it seems our nesting technique is insensitive to differences in the parent and nested model solutions.

[42] The model skill assessment was based on the salinity due to its major role in the shelf stratification. Temperature, however, also gives an important contribution to the stratification, especially during the summer months [*Li et al.*, 2012]. For this reason, the skill was also calculated based

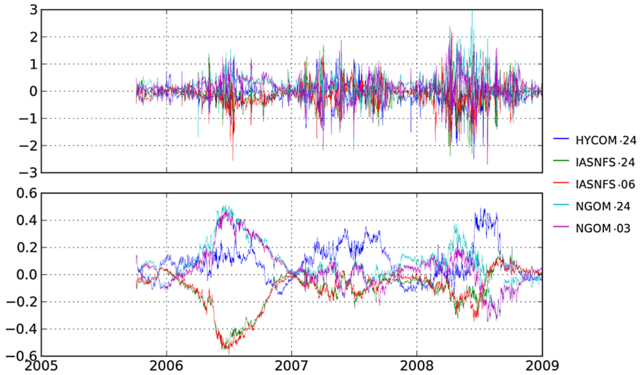

Figure 8. Sea surface salinity noise of the nested configurations: (upper panel) at LUMCON C6 station (indicated as C6 in Figure 1); (lower panel) average surface salinity of the whole domain. Note the factor of 5 change in scale between the lower and upper panels. The noise initial time is constrained by NGOM model output, which is only available from 5 October 2005.

on the temperature. We find that the model skill is extremely sensitive to the metric of comparison. In this study, we see marked differences in the model's ability to reproduce salinity and temperature fields. Salinity is influenced strongly by lateral advective processes, and the reproduction of the salinity field is improved when offshore eddies are able to enhance export freshwater from the shelf. Here nesting improves the model skill as compared to both the climatological and the parent models in the measurement region. Temperature is influenced by different processes—primarily surface heat fluxes and vertical mixing—and it is not clear that nesting improves further the model's reproduction of the temperature field. Also, we find that, for the salinity field, nesting improves the model performance, but it does not matter which parent model is used, *Fennel et al.* [2013] find that simulations of bottom hypoxia are very sensitive to the parent model.

[43] Because the wind, surface heat flux, and river forcing within the domain of the nested models is identical, differences in the simulations must be due to different exchanges of water masses through the open boundaries influenced by the different parent models. Figure 6 shows that, generally, the nested models are all relatively similar to each other when compared with the simulation with climatological boundary conditions; the exception is the eastern boundary freshwater flux, particularly from the simulation nested within HYCOM. This boundary is very close to the Mississippi delta, and the freshwater flux is sensitive to the numerical implementation of the river in each parent model. HYCOM, for example, does not use a true mass flux approach but rather applies the river discharge as an excess precipitation.

[44] However, the largest fluxes and the largest difference between climatological and nested boundary conditions are along the southern and western boundaries. The southern boundary shows net import of freshwater in the climatological boundary conditions. This may be because the climatology, based on historical hydrographic survey data, is influenced by the presence of the Mississippi/Atchafalaya plume system and thus contains a representation of the mean plume properties along the boundary. Inflowing water at the boundaries will, then, carry some spurious freshwater into the domain.

[45] Along the western boundary, the climatological simulation shows a much larger, persistent export of freshwater out of the domain than any of the nested models. The nested models all show an import of freshwater into the domain during summer, indicating that the freshwater plume over Texas (outside of the domain) is traveling upcoast, supplying the Louisiana shelf with an additional source of freshwater.

[46] Based on a numerical model skill assessment, *Hetland and DiMarco* [2012] hypothesized that a field of small-scale eddies existed over the Louisiana shelf and that these eddies created a noise floor, lowering the maximum skill that could be achieved by a numerical simulation. The present simulations show through two ensemble simulations the spatial and temporal structure of the small-scale eddy activity over the Louisiana shelf. The first ensemble experiment (Figure 7) perturbed the local forcing, keeping the boundary conditions constant. This experiment shows that the relative noise is much greater in summer than in winter. Also, it shows that the noise is greatest on the midshelf and outer shelf, between 50 and 200 m depth. This location is approximately coincident with the location of the outer edge of the Mississippi/Atchafalaya river plume front. Thus, it seems that the front is susceptible to instability in summer, during upwelling. In winter, during downwelling winds, there is still some evidence of instability along the plume front, but it is much reduced in magnitude and spatial extent. The second ensemble experiment demonstrated that these same instability processes can be triggered by using different boundary conditions. Figure 8 shows the interannual variability between the different nested models, demonstrating that the temporal structure of differences between the various nested models are seasonal in the same way as the first ensemble experiment.

5. Conclusion

[47] This study demonstrated the feasibility of using nested models in regional simulations. The nested models showed improved skill over regional model with climatological boundary conditions and the parent models over the same region. The nested modeling approach was also demonstrated to be flexible, because the nested models used different local forcing than the parent models. Thus, it is not only unnecessary to use identical forcing in both parent and nested models, as using different ones even resulted in higher nested model skill.

[48] Although nesting generally improved model skill scores when compared to observed hydrographic survey salinity fields, it did not matter which parent model was used for nesting. All nested models had similar skill scores, indicating that nesting is important, but it does not matter which parent model is used. Note that all of the models used assimilated satellite-derived sea surface altimeter information, so all parent models contained an accurate representation of the LC and LC eddies, the dominant circulation feature in the Gulf of Mexico.

[49] Instabilities along the edge of the Mississippi/Atchafalaya plume front create noises that would degrade the maximum skill for model prediction. Models using either

slightly different local or boundary condition forcing show that differences in surface salinity between the models can be as large or larger than the variance in the surface salinity itself during summer upwelling when the instabilities are most prevalent. During downwelling conditions in non-summer, the instabilities are suppressed. It is not yet clear why these instabilities are strongest in summer, but we hypothesize that it has something to do with the structure of the plume during upwelling conditions. During downwelling, the plume front may be stabilized through either increased vertical mixing caused by increased atmospheric frontal activity or the tilting of the isopycnals toward vertical because of the downwelling winds.

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